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GEOLOGIC TIME, AS INDICATED BY THE SEDIMENTARY ROCKS OF NORTH AMERICA.*

INTRODUCTION.

OF ALL subjects of speculative geology few are more attractive or more uncertain in positive results than geologic time. The physicists have drawn the lines closer and closer until the geologist is told that he must bring his estimates of the age of the earth within a limit of from ten to thirty millions of years. The geologist masses his observations and replies that more time is required, and suggests to the physicist that there may be an error somewhere in his data or the method of his treatment. The geologist realizes that geologic time cannot be reduced to actual time in decades or centuries; there are too many partially recognized or altogether unknown factors; but he can approximate the relative position of certain formations, and by comparison of their sediments, dimensions, and contained record of life with estimated rates of denudation, sedimentation and organic growth, form a general estimate of their relative time duration. It is my purpose to-day to take up the consideration of the evidence afforded by the sedimentary rocks of our continental area, and largely of a distinct basin of sedimentation, with a view of arriving, if possible, at an approximate time-period for their deposition. Before so doing, I will briefly refer to a few of the opinions that have been held by geologists on geologic

* Vice-Presidential address delivered before Section E, Am. Assc. Adv. Sci., Madison, Wis., August 17, 1893.

time and the age of the earth. Soon after geology emerged from its pre-systematic stage, in the latter part of the eighteenth century, and assumed an independent position among the inductive sciences speculations on the age of the earth began. Dr. James Hutton, the founder of modern physical geology, and the predecessor of Lyell, in advocating the uniformitarian theory, was the first to argue that the rate of destruction of one land area was the means of measuring the duration of others, and that the continents were formed of the ruins of pre-existing continents, but that in our measurement of time such periods were of indefinite duration.[1] It was not, however, until 1830, when Sir Charles Lyell published the results of his profound and philosophic studies of geologic phenomena, that the broad outlines of the law of uniformity, as opposed to the doctrine of geologic catastrophes, was fairly established. This work rendered possible a computation of the age of the earth on the principle that geologic processes were the same in the past as at present. He based his estimate of time on a rate of modification of species of mollusca since the beginning of the "Cambrian period," and divided the geologic series into twelve periods, assigning 20,000,000 years to each for a complete change in their species,—or 240,000,000 years in all. This estimate excluded the "antecedent Laurentian formation."[2]

The hour at our disposal does not permit of mentioning at length the views of other geologists. Dr. Charles Darwin thought that 200,000,000 of years could hardly be considered sufficient for the evolution of organic forms,[3] and Rev. Samuel Haughton assigned 1,280,000,000 of years to pre-Azoic time, and remarked that the globe was habitable, in part at least, for a longer period.[4] At a later date he estimated a minor limit to

[1] Theory of the Earth; or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe. Trans. Royal Soc. Edinburgh, Vol. I., 1788, pt. 1, p. 304.

[2] Principles of Geology, 10th Ed., Vol. I., 1867, p. 301.

[3] Origin of Species, American Ed., from 6th Eng. Ed., 1882, p. 286.

[4] Manual of Geology, 3rd Ed., 1871, p. 101.

geologic time of 200,000,000 of years.[1] Dr. James Croll estimated 72,000,000 years for the time duration since the first deposition of sedimentary rocks, while Sir Alfred R. Wallace thought that 28,000,000 years would suffice.[2] Of the value of this estimate he says: "It is not of course supposed that the calculation here given makes any approach to accuracy, but it is believed that it does indicate the order of magnitude of the time required."[3] Dr. Alexander Winchell reduced geologic time still more in his estimate of 3,000,000 years for the whole incrusted age of the world.[4] Later writers, however, do not accept this, as we find Sir Archibald Geikie concluding on the basis of denudation and deposition that the sedimentary rocks would have required 73,000,000 of years for their deposition, if denudation was at the rate of one foot in 730 years; or of 680,000,000 of years if at the slower rate of one foot in 6,800 years.[5] Mr. T. Mellard Reade adopted one foot in 3,000 years as the rate of average denudation throughout geologic time, and obtained a result of 95,000,000 of years as the time that had elapsed since the beginning of Cambrian time.[6] M. A. de Lapparent is one of the few European continental geologists that has written on geologic time. On the basis of mechanical denudation and sedimentation he thinks that from 67,000,000 to 90,000,000 of years would suffice, at the present rate of sedimentation for everything that has been produced since the consolidation of the crust.[7] The two most recent writers who have taken their initial datum point or "geochrone" from the consideration of late Cenozoic or Pleistocene phenomena

[1] Nature, Vol. 18, 1878, pp. 267–268.

[2] Stella Evolution and its Relations to Geological Time, 1889, pp. 48–49.

[3] Island Life, 2d. Ed., 1892, pp. 222–223.

[4] World Life, or Comparative Geology. Chicago, 1883, p. 378.

[5] Presidential Address; report of 62d meeting British Assoc. Adv. Sci., 1892, p. 21.

[6] Measurement of Geological Time. Geol. Mag., Vol. 10, 1893, pp. 99–100.

[7] De la mesure du temps parles phénomènes de sédimentation. Bull. Soc. Geol. France, 3d ser., Vol. 18, 1890, pp. 351–355. La Destinée de la terre férme et durée des temps geologiques. Revue des questions scientifiques, July, 1891. Pamphlet. Bruxelles. Pp. 1–38.

have differed materially in their results. Mr. W J McGee estimated that the mean age of the earth is 15,000 million years, and that 7,000 million had elapsed since the beginning of Paleozoic time.[1] In a subsequent note he modifies this conclusion and gives as a mean estimate 6,000 million years, of which 2,400 million have elapsed since the beginning of the Paleozoic. This is based on a minimum estimate of the age of the earth of 10,000,000 years and a maximum estimate of five million million (5,000,000,000,000) years.[2] Professor Warren Upham concludes that Quartenary time comprises about 100,000 years. He applies Professor Dana's time-ratio, and finds on this basis that the time needed for the earth's stratified rocks and the unfolding of its plant and animal life must be about 100 millions of years.[3]

From the foregoing estimates of geologic time the only conclusion that can be drawn is that the earth is *very old*, and that man's occupation of it is but a day's span as compared with the eons that have elapsed since the first consolidation of the rocks with which the geologist is acquainted.

When I began the preparation of this paper it was my intention to carefully analyze the sedimentary rocks of the entire geological series as exposed upon the North American continent. I soon found, however, that the time at my disposal would make this impracticable, and I decided to take up the history of the deposits that accumulated in Paleozoic time on the western side of our continent, in an area that for convenience I shall call the Cordilleran sea. This was chosen as (1) I was personally acquainted with many of its typical sections; (2) there was a broad and almost uninterrupted sedimentation during Paleozoic time; and (3) there is a prospect for obtaining more satisfactory data as a basis of calculation, since calcareous deposits are in excess of those of mechanical origin.

We will now consider certain points in relation to the growth

[1] American Anthropologist, Vol. 5, 1892, p. 340.

[2] Science, Vol. 21, 1893, p. 309.

[3] Am. Jour. Sci., Vol. 45, 1893, pp. 217–218.

or evolution of the North American continent, as the deposition of mechanical sediments depends to a considerable extent on the character of the adjoining land area, and chemical sedimentation is also influenced by it.

GROWTH OF THE CONTINENT.

The Algonkian sediments were deposited in interior and bordering seas that filled the depressions and extended over the margins of the American continent. From the great thickness of mechanical sediments it was evidently a period of elevated land and rapid denudation. With the close of Algonkian time extensive orographic movements occurred that outlined the subsequent development of the continent. The lines of the Rocky Mountain and Appalachian ranges were determined, and the great basins of sedimentation west of them defined. Subsequent movements have elevated the old and formed new sub-parallel ranges. These movements were often of long duration and also separated by great intervals of time, as is shown by the long-continued base levels of erosion during which the great thickness of calcareous deposits accumulated in the Cordilleran and Appalachian seas. Since Algonkian time the growth of the continent has been by the deposition of sediments in the bordering oceans and interior seas and lakes within the limits of the continental plateau; and it is considered that the relative position of the continental plateau and the deep sea have not materially changed during that period. How much the deposits on the continental border have increased its area is unknown, as at present they are largely concealed beneath the waters of the ocean. During Paleozoic time the two areas of greatest known accumulation were in the Appalachian and Cordilleran seas, where 30,000 feet or more of sediments were deposited. In the Cordilleran sea sedimentation was practically uninterrupted (except during a short interval in middle Ordovician time) until towards the close of Paleozoic time. In the northern Appalachian sea it continued without any marked unconformity, from early Cambrian to the close of Ordovician time, and, south of New York, with

relatively little interruption, until the close of Paleozoic time. Certain minor disturbances occurred along the eastern border of the sea, but they were not of sufficient extent to affect a general conclusion—which is, that the depression of the areas of deposition within the continental platform continued without reversal of the subsidence during Paleozoic time. During Cambrian, and it may be late Algonkian time, the extended interior Mississippian region was practically leveled by denudation, the eroded material being carried into the Cordilleran and Appalachian seas, and, probably, to a sea to the south.

The sedimentation of the Mississippian area in Paleozoic time, between the Appalachian and the Cordilleran seas, was small as compared to that which accumulated in the latter. In Devonian time there does not appear to have been any sedimentation in the western portion of it west of the 94th meridian and east of the Cordilleran sea, and it was slight in the same interval in the Appalachian sea south of the 37th parallel.[1] There is little if any evidence in the sediments of Paleozoic time to show that they were deposited in the deep, open ocean; on the contrary, they were largely accumulated in partially enclosed seas or mediterraneans and on the borders of the continental plateau. The former is particularly true of the sedimentation of the Cordilleran and Appalachian seas and the broad Mississippian sea.

The close of the prolonged period of Paleozic sedimentation was brought about by what Dana has termed the "Appalachian revolution." The topography of the continent was more or less changed, and the conditions of sedimentation that followed were unlike those that preceded. This revolution raised above the sea level a considerable portion of the Cordilleran and the Appalachian sea-beds and also of the Mississippian sea, east of the 96th meridian and north of the 34th parallel.

[1] The non-occurrence of Devonian sediment has not yet been fully explained. It has been suggested that the sea beyond the reach of mechanical sedimentation was too deep for the deposition of calcareous deposits. It is more probable that the sea was shallow and an area of non-deposition, or that its bed was raised to form a low, level land surface at a base level of erosion that was subjected to very slight degradation.

In its effect it may be compared to the Algonkian revolution[1] that preceded the deposition of the Paleozoic sediments.

With the opening of new conditions the sedimentation of Mesozoic time began upon the Atlantic border and over large areas of the western half of the continent with the deposit of mechanical sediments—sands, silts, etc.—during Jura-Trias time. They are of a character that naturally follows a period of disturbance of pre-existing conditions, and the formation of new basins of deposition with more or less elevated adjoining land areas. At its close orographic movements affecting the positions of the beds occurred upon the Pacific and Atlantic coasts, and also, to a more limited degree, throughout the Rocky mountain region. This does not appear to have extended over the plateau region or the central belt between the 97th and 105th meridians.

The Cretaceous formations have their greatest development between the 97th and 112th meridians in Mexico and the United States, in a broad belt which extends from the boundary of the latter to the northwest into the British Possessions as far as the 61st parallel. They were of a marine origin until towards the close of the period when a prolonged orographic movement elevated a large area of the continent above sea level, and locally upturned the Cretaceous strata in the Rocky mountain area. The shoaling of the sea was followed by the formation of great inland lakes, in which fresh water deposits succeeded the marine and estuarian sediments. Over the coastal regions they were of marine origin throughout.

The Tertiary sediments deposited on the Cretaceous are marine on the Atlantic, Gulf of Mexico, and Pacific coasts, and of fresh-water origin in the Rocky mountain and Great Plains areas—where they were deposited in the great inland lakes outlined in the previous period.

[1] The term revolution is used to describe the culmination of a long series of phenomena that finally resulted in a distinctly marked epoch in the evolution of the continent. The "Appalachian revolution" began far back in the Paleozoic, and culminated in the later stages of the Carboniferous and the Algonkian revolution, probably began far back in Algonkian time.

GEOGRAPHIC CONDITIONS ACCOMPANYING THE DEPOSITION OF PALEOZOIC SEDIMENTS IN THE CORDILLERAN SEA.

The assumed area of the Cordilleran or Paleo-Rocky mountain sea includes over 400,000 square miles between the 35th and 55th parallels. To the eastward during lower and middle Cambrian time a land area is thought to have extended from east of the 111th meridian across the continent to the Paleo-Appalachian sea. This land was depressed toward the close of middle Cambrian time, and the Mississippian sea expanded over the wide plateau-like interior region, from the Gulf of Mexico on the south to the Lake Superior region on the north; westward it penetrated among the mountain ridges between the 105th and 111th meridians, laying down the upper Cambrian deposits that are now found in New Mexico, Arizona, eastern Utah, the western half of Colorado, Wyoming, Idaho and Montana, and still farther north into Alberta and British Columbia. During Ordovician, Silurian, Devonian, and Carboniferous time this entire Mississippian region, except portions in Devonian time, appears to have been covered by a relatively shallow sea that was co-extensive with the Appalachian sea and that communicated freely with the Cordilleran sea. During this same age, however, the Rocky mountain area of New Mexico, Colorado, Utah, Wyoming and Montana formed a more or less well-defined boundary of ridges and islands between the Cordilleran and the interior sea up to the 49th parallel. To the north of the latter the conditions appear to have been the same as on the eastern side of the continent, where the Appalachian sea communicated freely with the Mississippian sea. From the data that we now have I think that the Paleozoic (Mississippian) sea extended at times over nearly all of the area subsequently covered by the Cretaceous and the later formations between the Gulf of Mexico and the Arctic ocean. This belt is bounded almost continuously on the east and west by Paleozoic rocks that extend from the Arctic ocean to Mexico, and whether of Cambrian, Ordovician, Silurian or Devonian age they carry essentially the same fauna throughout their extent. In the outcrops of lower strata that rise up

through this Cretaceous area, the Cambrian, Ordovician, and Carboniferous rocks are found encircling the pre-Paleozoic rocks. Instances in which the Archean rocks have been met with immediately beneath the Cretaceous in borings in Dakota and Minnesota are along the eastern border of the area, next to the Archean rocks,—where it is probable that the Cretaceous overlaps the Paleozoic to the Archean.

The western side of the Cordilleran sea seems to have been bounded by a land area that separated it from the Paleozoic sea, which extended through central California and the Pacific border of British Columbia and Vancouver's Island. From the positions of the Carboniferous deposits of California at the present time it appears that this land varied from 100 to 150 miles in width and was practically continuous along the western side of the Cordilleran sea. This view is further strengthened by the fact that the Carboniferous fauna of California has certain characteristics which are not found in the Carboniferous of the Cordilleran area. Our knowledge of conditions north of the 55th parallel is limited by the want of accurate geologic data. If Cambrian and Carboniferous rocks were not deposited in the Mackenzie river basin and also on the eastern side of the area now covered by Cretaceous strata, the inference is that during Cambrian and Carboniferous time there was a land area to the east and north of the northern Cordilleran sea that may have been tributary to the latter.

SOURCE OF SEDIMENTS DEPOSITED IN THE CORDILLERAN SEA.

The sediments deposited in every sea or lake are derived from land areas either by mechanical or chemical denundation.

Mechanical denudation results from the action of the waves and currents along the shore and the agency of rain, frost, snow, ice, wind, heat, etc., on the land. Rain is the most important factor, and the result depends mainly upon its amount and the slope or the gradient of the land. The general average of denudation for the surface of the land areas of the globe, now usually accepted, is one foot in 3,000 years. This varies locally,

according to Sir Archibald Geikie, from one foot in 750 years to one foot in 6,000 years.[1] Of the rate of denudation during Paleozoic time about the Cordilleran sea we know very little, but I think that it was relatively rapid in early Cambrian time and during the deposition of the arenaceous sediments of the Ordovician and Carboniferous. The material forming the argillaceous shales of the Cambrian and Devonian was supplied to the sea more slowly. These conclusions are sustained by the slight change in the character of the faunas where interrupted by the sands and pebbles of the Ordovician and Carboniferous and the marked change between the base and summit of the argillaceous shales. As a whole I think we are justified in assuming a minimum rate of mechanical denudation—of considerably less than one foot in 1,000 years—for the area tributary to the Cordilleran sea.

Chemical denudation is the removal of material taken into solution by water. Mr. T. Mellard Reade has discussed this phase of denudation in an admirable manner.[2] He came to the conclusion, from what was known of the volume of water discharged into the ocean per year, the average amount of material in chemical solution and the area of land surface drained by the rivers, that an average of 100 tons of rocky matter is dissolved per English square mile per annum. Of this he says: "If we allot 50 tons to carbonate of lime, 20 tons to sulphate of lime, 7 to silica, 4 to carbonate of magnesia, 4 to sulphate of magnesia, 1 to peroxide of iron, 8 to chloride of sodium, and 6 to the alkaline carbonates and sulphates we shall probably be as near the truth as present data will allow us to come."[3] By the use of the data given by Mr. John Murray, in a paper on the total annual rainfall on the land of the globe, and the relation of rainfall to the discharge of rivers,[4] I obtain 113 tons as the total

[1] Brit. Assoc. Adv. Sci., Sixty-second Meeting, 1893, p. 21.

[2] Proc. Liverpool Geol. Soc., Vol. III., pt. 3, 1877, pp. 212–235. Chemical Denudation in Relation to Geological Time, 1879, pp. 1–61.

[3] Loc. cit., p. 229.

[4] Scottish Geol. Mag., Vol. III., 1887, pp. 65–77.

amount of matter in solution discharged into the Atlantic basin per annum from each square mile of area drained into it. Of this 49 tons consist of carbonate of lime and 5.5 tons of sulphate and phosphate of lime.[1]

Mechanical Sediments.—With the geographic conditions described as prevailing during Paleozoic time, the source of mechanical sediments later than the Middle Cambrian must have been from the broken area on the eastern side that extended 100 to 200 miles to the eastward and to a much greater extent from the land along the western side of the sea. The enormous deposit of from 10,000 to 20,000 feet of mechanical sediments in early Cambrian time is explained by the assumption of favorable topographic conditions of denudation following the Algonkian revolution and the presence of a land area over the interior portion of the continent, and also, in all probability, between the western side of the Cordilleran sea and the western border of the continent. During this period the conformable pre-fossiliferous strata of the Cambrian accumulated and about 6,000 feet of the lower fossiliferous rocks as they occur in the Eureka district of central Nevada. Following the depression of the continent, which carried down the central area and also introduced the upper Cambrian (Mississippian) sea into the Rocky mountain area of Colorado, etc., there were deposited of mechanical sediments in central Nevada:

Ordovician sands, - - - - - - -	500	feet.
Devonian fine argillaceous muds, - - -	2,000	"
Lower Carboniferous sands, - - - - -	3,000	"
Upper Carboniferous conglomerate and sands, - -	2,000	"
	7,500	"

making a total of 7,500 feet of mechanical sediments, the remaining portion of the section (15,150 feet) being limestone.

The following table exhibits the relative thickness of

[1] Total amount removed in solution per annum by rivers, 762,587 tons per cubic mile of river water. Total discharge of river water per annum into the Atlantic, 3,947 cubic miles. Area drained, 26,400,000 square miles. Amount of carbonate of lime per annum, 326,710 tons per cubic mile of river water; of sulphate and phosphate of lime, 37.274 tons.

mechanical and chemical deposits in the Cordilleran sea after the middle Cambrian subsidence :

	Wasatch.	Central Nevada.	Southwest Nevada.	Montana.	Alberta.
Mechanical Sediment, - -	10,000	7,500	2,500	1,000	4,600
Chemical Sediment, - -	10,400	15,150	13,000	4,000	15,000
Ratio, - - - - - -	$\frac{1}{1}$	$\frac{1}{2}$	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$

If an average is taken of the mechanical sediment deposited subsequent to the close of middle Cambrian time, it will be found to be about 5,000 feet for the entire area, which, I think, does away with any necessity to assume an additional hypothetical land area for the source of the mechanical sediment. The fine sand composing the quartzites and the silt forming the shales, as well as the fine conglomerate of later deposits, were derived from the adjoining land areas, and, in all probability, currents swept through from the ocean to the south or north, distributing the mud and sand contributed from the rivers and streams along the shores.

Chemical Sediments.—The present supply of the carbonate of lime, silica, etc., contained in sea-water is derived from waters poured into the sea by rivers and streams. The Cordilleran sea undoubtedly received a large contribution from the adjoining land areas, but a considerable amount was possibly derived from an oceanic current that circulated through it as the southern equatorial current of the Atlantic now sweeps through the Caribbean. From the vast deposits of carbonate of lime it might be assumed, *a priori*, that the waters of a Mississippi or Amazon were poured into it, but there is not any evidence of the existence of such a river, although the tributary area may have been very large in Cambrian and Carboniferous time, if the drainage of the country west of Hudson's Bay was to the westward.

Conditions of Deposition.—With free communication into the open ocean on the south, and probably on the north, during most of Paleozoic time strong currents must have circulated through the Cordilleran sea. The broad distribution of

mechanical sediments of a uniform character clearly shows this to have been the case, especially in pre-Silurian (Ordovician) time. The present known distribution of the mechanical sediments indicate that they were mainly brought into the sea from the west,[1] although a vast amount was derived from the land on the eastern side in pre-Ordovician time. They were quite evenly distributed over the sea bed, except where local accumulations of silt and sand occurred near the larger sources of supply, or in the direction of powerful currents within the sea.

The conditions of the deposition of the carbonate of lime are less clearly understood than those governing mechanical sediments, and I shall enter upon the discussion of them at considerable length. There are three methods by which it usually is considered that it may be deposited: 1. Agency of organisms; 2. Chemical precipitation; 3. By mechanical methods.

It is the general opinion of geologists that limestone rocks are the result almost entirely of the consolidation of lime removed from the sea water through the agency of life, and that they consist of the remains of foraminifera, crinoids, corals, etc., or their fragments, embedded in a more or less crystalline matrix resulting from subsequent alteration of the original deposits. This, however, has been seriously questioned. Sorby, in giving his general conclusions of an extensive microscopic examination of limestones, states that:

Even if it were possible to study in a detached state the finer granular particles which constitute so large a part of many limestone formations, it would usually be impossible to say whether they had been derived from organisms which can decay down into granules, or from other organisms which can only be worn down into granules, or from ground-down older limestone, or, in some cases, from carbonate of lime deposited chemically as granules. . . . . The shape and character of the identifiable fragments do, indeed, *prove* that much of this must have been derived from the decayed and worn-down calcareous organisms;

[1] Geol. Expl. Fortieth Parallel, Vol. I., 1878, p. 247.

and very often we may reasonably *infer* that the greater part, if not the whole, was so derived; but, at the same time, it is impossible to *prove*, from the structure of the rock, whether some or how much was derived from limestones or earlier date, or was deposited chemically, as some certainly must have been.[1]

In their memoir on coral reefs and other carbonate of lime formations in modern seas, Messrs. Murray and Irvine show that temperature of the water has a controlling influence upon the abundance of species and individuals of lime-secreting organisms; high temperature is more favorable to abundant secretions of carbonate of lime than high salinity.[2]

Taking the samples of deep sea deposits collected by the Challenger as a guide, the average percentage of carbonate of lime in the whole of the deposit covering the floor of the ocean is 36.83; of this it is estimated that fully 90 per cent. is derived from pelagic organisms that have fallen from the surface water, the remainder of the carbonate of lime having been secreted by organisms that laid on, or were attached to, the bottom. The estimated area of the various kinds of deposits, the average depth, and the average percentage of carbonate of lime to each are shown in the following table:

TABLE showing the Estimated Area, Mean Depth, and Mean Percentage of $CaCO_3$, of the different Deposits.

Deposit.		Area square miles.	Mean depth in fathoms.	Mean per ct. of $CaCO_3$.
Oceanic Oozes and Clays	Red clay,	50,289,600	2727	6.70
	Radiolarian ooze,	2,790,400	2894	4.01
	Diatom ooze,	10,420,600	1477	22.96
	Globigerina ooze,	47,752,500	1996	64.53
	Pteropod ooze	887,100	1118	79.26
Terrigenous Deposits	Coral sands and muds,	3,219,800	710	86.41
	Other terrigenous deposits, blue mud, etc.	27,899,300	1016	19.20

Loc. cit., p. 82.

"We have little knowledge as to the thickness of these deposits, still such as we have goes to show that in these organic cal-

[1] Quart. Jour. Geol. Soc. London, Vol. 35, 1879, pp. 61–92.

[2] Proc. Roy. Soc. Edinburgh, Vol. 17, 1890, p. 81.

careous oozes and muds, we have a vast formation greatly exceeding in bulk and extent the coral reefs of tropical seas; they are most widely distributed in equatorial regions, but some patches of Globigerina ooze are to be found even within the Arctic circle in the course of the gulf stream."[1]

The percentage of carbonate of lime contained in deposits accumulating at different depths, as obtained from 231 samples collected by the Challenger, is shown in the following tabulation:

14	cases	under	500	fathoms,	m. p. c.	86.04
7	"	"	500 to 1000	"	"	66.86
24	"	"	1000 to 1500	"	"	70.87
42	"	"	1500 to 2000	"	"	69.55
68	"	"	2000 to 2500	"	"	46.73
65	"	"	2500 to 3000	"	"	17.36
8	"	"	3000 to 3500	"	"	0.88
2	"	"	3500 to 4000	"	"	0.00
1	"	"	4000	"	"	trace.

The fourteen samples under 500 fathoms are chiefly coral muds and sands, and the seven samples from 500 to 1000 fathoms contain a considerable quantity of mineral particles from continents or volcanic islands. In all the depths greater than 1000 fathoms the carbonate of lime is mostly derived from the shells of pelagic organisms that have fallen from the surface waters, and it will be noticed that these wholly disappear from the greater depths.[2]

By a series of experiments Messrs. Murray and Irvine found: "That although sea water under certain conditions may take up a considerable quantity of carbonate of lime in solution, yet it is unable permanently to retain in solution more than is usually found to be present in sea water, and it is owing to this that the amount of carbonate of lime is so constantly low. The reaction between organic matter and the sulphates present in sea water (to which we have referred) tends also to keep the amount of carbonate of lime in solution at about one-half (0.12 grms.) of what it might contain (0.28 grms. per litre). This peculiarity of sea water, in taking up a large amount of amorphous carbon-

[1] Loc. cit., pp. 82–83.

[2] Loc. cit., p. 84.

ate of lime and throwing it out in the crystalline form, accounts for the filling up of the interstices of massive coral with crystalline carbonate in coral islands and other calcareous formations, so that all traces may ultimately be lost of the original organic structure."[1]

The authors explain the disappearance of shells and lime deposits in the greater depths of the ocean by their being dissolved by the carbonic acid in the water, which is present in larger quantity at great depths and also is produced by the decomposition of the animal matter of the shell and of the various organisms living in the water and on the bottom. They conclude that:

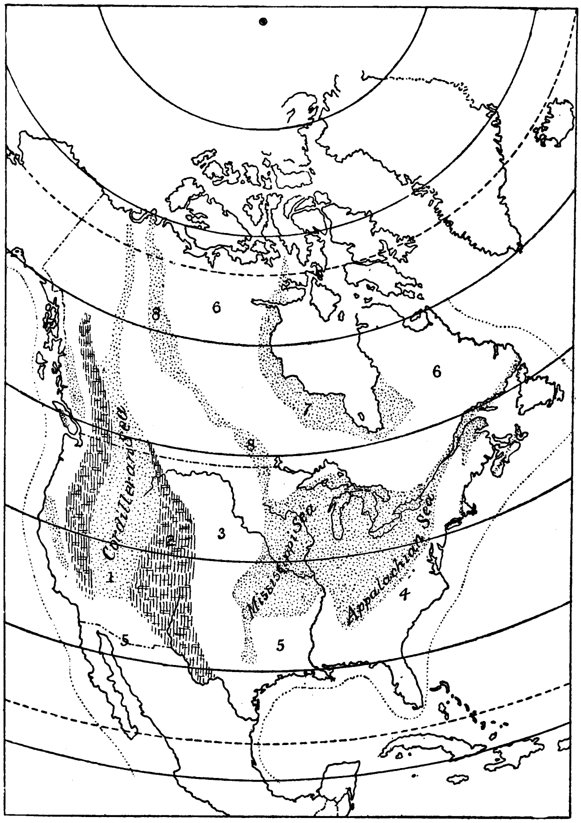
On the whole, however, the quantity of carbonate of lime that is secreted by animals must exceed what is re-dissolved by the action of sea water, and at the present time there is a vast accumulation of the carbonate of lime going on in the ocean. It has been the same in the past, for with a few insignificant exceptions all the carbonate of lime in the geological series of rocks has been secreted from sea water, and owes its origin to organisms in the same way as the carbon of the carboniferous formations; the extent of these deposits appears to have increased from the earliest down to the present geological period.[2]

In their report on deep sea deposits, collected by the Challenger Expedition, Messrs. Murray and Renard state that the chemical products formed in situ on the floor of the ocean nearly all originate in a sort of broth or ooze, in which the sea water is but slowly renewed. Many of them appear to be formed at the surface of the deposit—at the line separating the ooze from the superincumbent water, where oxidation takes place. In the deeper layers of the deposit a reduction of the higher oxides frequently occurs, and at the surface of the mud or ooze there are many living animals, as well as the dead remains of surface plants and animals.[3]

[1] Loc. cit., pp. 94–95.

[2] Loc. cit., p. 100.

[3] Report on the Scientific Results of the Voyage of M. M. S. Challenger. Deep-Sea Deposits, 1891, p. 337.



DESCRIPTION OF MAP.

On the map the hypothetical areas of the Cordilleran, Mississippian and Appalachian seas are clearly indicated. The land area west of the Cordilleran sea is numbered No. 1. The Californian sea and the area of Paleozoic deposits of western British Columbia No. 10. The northern extension of the Cordilleran sea (No. 9) is continued as the Paleozoic-devonian sea to the Arctic ocean. The early Cambrian land area (No. 2) east of the Cordilleran sea must have been more or less covered by water during later Paleozoic time. The area now covered by Mesozoic deposits, indicated by No. 3, was presumably covered by the westward and northward extension of the Paleozoic-Mississippian sea. The area east of the Appalachian sea is indicated by No. 4; and the supposed land barrier between the Hudson Bay and the Mississippian sea by No. 6; it is not improbable that during Ordovician or Silurian time a sea may have connected the two latter seas. The region to the south, indicated by No. 5, is supposed to have been covered by the southward extension of the Appalachian, Mississippian and Cordilleran seas. It is now covered by deposits of Mesozoic and Cenozoic seas.

A more detailed description of the map can be gained from the section on the growth of the continent and on the geographic conditions accompanying the different depositions of Paleozoic sediments in the Cordilleran sea.

They also conclude that practically all the carbon of marine organisms must ultimately be resolved into carbonic acid, the quantity of that acid produced in this way must be enormous, and cannot but exert a great solvent action not only on the dead calcareous structure, but also on the minerals in the muds on the floor of the ocean.[1] Of the effect of this destructive action, they say: "In all cases, however, calcareous structures of all kinds are slowly removed from the bottom of the ocean on the death of the organisms, unless rapidly covered up by the accumulating deposits, and in this way protected to a certain extent from the solvent action of the sea-water. It is evident from the Challenger investigations that whole classes of animals with hard calcareous shells and skeletons, remains of which one might suppose would be preserved in modern deposits, are not there represented; although they are now living in immense numbers in the surface waters or on the deposits at the bottom in some regions, yet all traces of them have been removed by solution. A similar removal of calcareous organic structures has undoubtedly taken place in the marine formations of past geologic ages.[2]

From the preceding statements it is evident that initially the greater part of the carbonate of lime is taken from the sea water by organic agency, but in the working over of this material in the chemical laboratory at the bottom of the sea a considerable portion is taken up by the sea water as amorphous carbonate of lime and thrown out in the crystalline form to form the matrix of the undissolved shells, etc.[3]

Mr. Bailey Willis has recently studied the question of the deposition of carbonate of lime, and states that "chemists describe two conditions under which bicarbonate of lime may be decomposed into neutral carbonate and carbonic acid: 1st, by diminution of the tension of the carbonic acid in the atmosphere; 2nd, by agitation of the solution."

[1] Loc. cit., p. 255.

[2] Loc. cit., p. 277. In this connection I wish to ask the student to read Messrs. Murray and Irvine's remarks on pp. 97-99, Proc. Roy. Soc., Edinburgh, Vol. 17, 1890.

[3] Proc. Roy. Soc., Edinburgh, Vol. 17, 1890, pp. 94-95.

"Theoretically either one of three things may occur to the neutral carbonate of lime, if it be thrown out of solution by either one of these processes. The carbonate may be redissolved, deposited as a calcareous mud, or built into organic structure." He studied some recent limestone deposited in the Everglades of southern Florida and found it to be formed of fragments of shells embedded in calcite. He states that, "Under the microscope the unaltered structure of the organic fragments is strikingly different from that of the coarse holocrystalline matrix, in which it is apparent that the crystals developed in place. Were this a limestone of some past geologic period it would be concluded, on the evidence of the crystalline texture of some parts of it, that it had been metamorphosed, and that the organic remains now visible had escaped the process which altered the matrix. But the observed conditions of its formation preclude the hypothesis of secondary crystallization."[1] Apparently the crystalline matrix is one primary product, and the calcareous mud is another, which being precipitated in the solution remains an incoherent sediment.

I think we may accept the conclusion that the deposition of carbonate of lime is by both organic agency and chemical precipitation. It is not necessary to speak of deposition by mechanical methods except in relation to the deposition of chemically derived granules. This probably takes place, and may be a very important factor in the formation of limestones in seas receiving a large supply of calcium from the land. Calcareous conglomerates do not enter as a prominent deposit in the Cordilleran area.

There is no evidence in the marine, geologic formations of this continent that they were deposited in the deep sea; on the contrary they are unlike such deposits and bear positive evidence of having been laid down in relatively shallow waters. Limestones with ripple-marks and sun cracks occur, and beds of ripple-marked sandstones alternate with shales and limestones. The more massive limestones, however, appear to have accumulated in deeper water. The conditions in the Cordilleran sea

[1] See Mr. Willis' article in Journal of Geology, Chicago, September, 1893.

were, I think, more favorable for rapid deposition than in the deep open ocean, but probably not as favorable as about coral reefs and islands. The limestones, and often the contained fossils, clearly indicate the presence of many of the same conditions of deposition as described by the authors I have quoted. More or less decomposed shells occur in nearly every limestone and a large proportion of limestone ; especially the non-metamorphic marbles clearly show that they were deposited under the influence of the agencies at work in the laboratory of the sea. Willis states that this occurs in the shallow waters of the Everglades of Florida, and there is no *a priori* reason why it did not occur throughout geologic time,—on the contrary, there is no doubt that it did.

Rate of deposit in former times.—It has frequently been assumed that in the earlier epochs the conditions were more favorable for rapid denudation, and in consequence thereof the transportation and deposition of sediment was greater. Professor Prestwich considers[1] that prior to the sedimentary rocks the land surface consisted of crystalline or igneous rocks subject to rapid decomposition owing to the composition of the atmosphere and to their inherent tendency to decay. They must have yielded to wear and removal with a facility unknown amongst mechanically formed and detrital strata where erosion operates. He thus accounts for one of the factors that gave the large dimensions and thicknesses of the earlier formations. Mr. Wallace thinks that geological change was probably greater in very remote times,[2] stating that all tellurac action increases as we go back into the past time, and that all the forces that have brought about geological phenomena were greater.[3]

[1] Geology, Vol. 1, 1886, pp. 60-61.

[2] Island Life, 2nd Ed., 1892, pp. 223-224.

[3] Sir William Thompson (Lord Kelvin), inferred from his investigations upon the cooling of the earth, that the general climate cannot be sensibly affected by conducted heat at any time more than 10,000 years after the commencement of the superficial solidification. Treatise on Natural Philosophy, Cambridge, 1883, Vol. 1, pt. 2, p. 478. Of the degree of the sun's heat we know so little that conjectures in relation to it have little force against the conditions indicated by the sedimentary rocks and their contained organic remains.

Dr. Woodward says, on the opposite view, that in the earliest geological periods each bed of sand, clay, limestone, etc., had actually to be formed, and that later deposits had the older sedimentary ones to furnish material, and, therefore, the newer deposits were laid down more rapidly.[1] This does not impress me strongly ; but from my experience among the Paleozoic rocks I agree with Sir A. Geikie, that "We can see no proof whatever, nor ever any evidence which suggests that on the whole the rate of waste and sedimentation was more rapid during Mesozoic and Paleozoic time than it is to-day.[2]

Professor Huxley, in his presidential address to the Geological Society of London in 1870, treats of the distribution of animals and says of his hypothesis that it "requires no supposition that the rate of change in organic life has been either greater or less in ancient times than it is now ; nor any assumption, either physical or biological, which has not its justification in analogous phenomena of existing nature."[3]

In the Grand Cañon of the Colorado, Arizona, there are 11,950 feet of strata of Algonkian age extending unconformably beneath the Cambrian. There is nothing in this section to indicate that the conditions of deposition were unlike those of the strata of Paleozoic and Mesozoic time. The sandstones, shales, and limestones are identical in appearance and characteristics with those of the latter epoch. The deposition of sulphate of lime and gypsum occurred abundantly in the upper portions of the series, and salt is collected by the Indians from the deposits formed by the saline waters issuing from the sandstone 8,000 feet below the summit of the series. The sandstone and shales were deposited in thin, even laminæ and layers, and the sun cracks and ripple marks give evidence of slow, uniform deposition. In the upper part of Chuar terrane there are 235 feet of limestone. And in one of the layers of limestone, 2,700 feet below the summit of the Chuar terrane, I find abundant evidence of the pres-

[1] Geol. England and Wales, 2nd Ed., 1887, p. 23.

[2] Rept. Sixty-second Meeting Brit. Assoc. Adv. Sci., 1892, p. 19.

[3] Quart. Jour. Geol. Soc., Vol. 26, 1870, p. lxiii.

ence of spiculæ of sponges, and what appear to be worn fragments of some small fossils. There is absolutely nothing to indicate more rapid denudation and corresponding deposition in this early pre-Cambrian series than we find in the Paleozoic, Mesozoic or Cenozoic formations.

PALEOZOIC SEDIMENTS OF THE CORDILLERAN SEA.

The great sections of sedimentary rocks in Arizona, Nevada, Utah, Montana, and in Alberta, B. A., all bear evidence that the sediments of which they are built up were deposited in a connected and continuous sea that extended from the vicinity of the 34th parallel, on the south, to the Arctic ocean on the north. Judging from the data now available, the width of this sea varied from 300 miles in Nevada to 500 miles on the line of the 40th parallel, and, with interruptions by mountain ridges, to 250 miles on the 49th parallel. It appears to have narrowed to the north in Alberta, British Columbia. Roughly computed, it covered south of the 55th parallel 400,000 square miles exclusive of any extension westward into northern-central California and southwestern Oregon and to the eastward over the area subsequently covered by the great interior Cretaceous sea. There is also an addition that might be made to allow for the contraction of the area by the later north-and-south faults and thrusts. Dr. G. M. Dawson estimates that in the Alberta and British Columbia area the width of the zone of the Paleozoic rocks has probably been reduced one-half by the folding and faulting, or from 200 to 100 miles.[1] This area assumed for the Cordilleran sea is on this account probably one-half less than it was before the Appalachian revolution.

The Wasatch section, on the eastern side of the area under consideration, has 30,000 feet of strata, of which 10,400 feet are limestone.[2] Further to the west, 250 miles W.S.W., at Eureka, Nevada, there 30,000 feet of strata in the entire section, and of this amount 19,000 feet are referred to limestone.[3] In the Pahranagat range and vicinity, 200 miles south of the Eureka section,[4]

[1] Bull. Geol. Soc. Am., Vol. 2, 1891, p. 176.

[2] Geol. Expl. Fortieth Parallel, Vol. 1, 1878, pp. 155-156.

[3] Mon. U. S. Geol. Survey, Vol. 20, 1892, p. 178.

[4] Loc. cit. pp. 186-200.

the limestones of the Paleozoic measure over 13,000 feet in a section of 13,500 feet. This section includes only 350 feet of the upper beds of the lower quartzite series, which is upwards of 11,000 feet in thickness in the Schell Creek range of eastern Nevada.[1]

On the eastern side of the area, in Montana, 300 miles north of the Wasatch section of Utah, the deposit of Paleozoic sediment is less in volume. Dr. A. C. Peale's section gives 3,800 feet of limestone in 5,000 feet of strata.[2] This does not include the 6,000 feet or more of sediments that occur below the fossiliferous Cambrian. I believe that the Paleozoic section will be found to be considerably thicker to the westward in Idaho. Continuing to the north 450 miles, the sections measured by Mr. R. G. McConnell, give 29,000 feet of Paleozoic strata, including 14,000 feet of limestone[3]. In a "Note on the Geological Structure of the Selkirk Range," Dr. Geo. M. Dawson describes a section containing upwards of 40,000 feet of mechanical sediments, which he refers largely to the Cambrian[4].

The Paleozoic limestones extend to the north, on the line of the eastern Rocky Mountains, to the Arctic ocean. In latitude 55° to 60° N. the Devonian limestones are over 2,500 feet in thickness, and there other still lower Paleozoic rocks that have not yet been studied in detail. The Devonian limestones extend 700 miles in the valley of the Mackenzie, from Great Slave Lake to below Fort Good Hope.[5] No Carboniferous limestones have been described from this region.

Tabulating the sections south from the 55th parallel and allowing for a great thinning out of the sediments in Idaho and Montana, we obtain an approximate general average of 21,000 feet of strata, of which 6,000 feet are limestone over an area estimated to include 400,000 square miles. Each square mile

[1] Geol. and Geog. Surveys West of 100th Merid., Vol. 3; Geology, 1875, p. 167.

[2] Author's manuscript.

[3] Geol. and Nat. Hist. Sur. Canada; Am. Rep., 1866, pp. 17, D–30 D.

[4] Bull. Geo. Soc. Am. Vol. 2, 1891, p. 168.

[5] Rept. Expl. Yukon and Mackenzie Rivers Basins, N. W. Terr. Geolo. & Nat. Hist. Sur. Canada, Vol. 4 (1888–'89), 1890, pp. 13 D–18 D.

includes 27,878,400 cubic feet of limestone for each foot in thickness and 167,270,400,000 cubic feet for a thickness of 6,000 feet, which, with an average of 12.5 cubic feet to ton, gives 13,381,632,000 tons of limestone and impurities per square mile. The result of ten analyses of clear limestones within the central portion of area gives an average of 76.5 per cent. of carbonate of lime.[1] Taking 75 per cent. as the proportion of pure carbonate of lime (after deducting 50 per cent. to allow for arenaceous and argillaceous material in partings of strata, etc.), there remain 5,018,112,000 tons per square mile; multiplying this by 400,000 the result gives the number of tons of carbonate of lime that were deposited in what we know of the Cordilleran sea in Paleozoic time, or 2,007,244,800,000,000 tons, or two billion million tons in round numbers.

The following mode of presentation of the above was suggested by Mr. Willis:

In order to proceed with a calculation of the period required to form this thickness of 15,000 feet of mechanical sediment plus 6,000 feet of calcareous sediment, it is necessary, 1st, to compute the cubic volumes of the sediments; 2d, to estimate the area from which they were derived; and, 3d, to divide the cubic contents of the sediments by this land area. The result thus obtained represents the depth of erosion required to furnish the whole deposit, from which we may estimate the time under different assumptions of the rate of erosion.

But if we express amounts in cubic feet or tons the figures pass all comprehension; therefore, to simplify the statement, it is well to use a mile-foot as the unit of volume, that is, the volume of one mile square and one foot thick. (1 mile-foot=.79 Kilometre-metres). This is equal to 223,000 tons, if 12½ cubic feet of limestone equal one ton.

Thus stated mechanical sediments covering 400,000 square miles and 15,000 feet thick contain 6 billion mile-feet (4,740 million Kilometre-metres); and calcareous sediments covering the same area and 6,000 feet thick correspond to 2 billion 4 hundred million mile-feet (1,896 million Kilometre-metres). In the calcareous sediments a liberal allowance of one-half may be made for arenaceous and argillaceous matter in the limestone and partings, and analyses of ten clear limestones within the central part of the area give a little more than 75 per cent. of carbonate of lime. Applying these reductions we get 900 million mile feet (711 million Kilometre-metres) of pure carbonate of lime.

DURATION OF PALEOZOIC TIME IN THE CORDILLERAN AREA.

Estimates from Mechanical Sedimentation.—The land area tributary to the Cordilleran sea was larger before the depression of

[1] Geol. Expl. Fortieth Par. Vol. 2; Mon. U. S. Geol. Survey, Vol. 20.

the continent, towards the close of middle Cambrian time than during subsequent Paleozoic time. It included a portion of the region to the eastward and probably a belt of land extending well towards the Pacific coast of the continental plateau. The interior (Mississippian) region, west of the 90th meridian, probably drained into the sea to the south, forming a Cambrian Mississippi river prior to middle Cambrian time. This limits the Cambrian drainage into the Cordilleran sea to an area estimated at 1,600,000 square miles. The average thickness of mechanical sediments deposited before upper Cambrian time is estimated at from 10,000 to 15,000 feet. Taking the minimum of 10,000 feet and the assumed drainage area of 1,600,000 square miles and the rate of denudation at one foot in 1,000 years, it would have required 2,500,000 years to carry to the sea and distribute the 10,000 feet of sediment. This means the deposition of .048 of an inch per year, which is very small if the supposed conditions of denudation and transportation were as favorable as the character and mode of occurrence of the sediments indicate. If one-fourth of an inch per year is assumed as the rate of deposition, the 10,000 feet of sediment would have accumulated in 480,000 years or, in round numbers, in 500,000 years, which increases the rate of denudation to one foot in 200 years.[1]

CAMBRIAN MECHANICAL SEDIMENTS.

Rate of erosion over land area of 1,600,000 square miles.	Time in years for erosion of 2,500 feet.	Rate of deposition over sea area of 400,000 square miles for strata 10,000 feet thick.
1 foot in 3,000 years, - -	7,500,000	1 foot in 750 years, or .016 inch per annum.
1 foot in 1,000 years, - -	2,500,000	1 foot in 250 years, or .048 inch per annum.
1 foot in 200 years - - -	500,000	1 foot in 50 years, or .24 inch per annum.

In view of the evidence of rapid accumulation contained in the strata themselves the most rapid rate of deposition here stated, namely, .24 inch per annum, is considered as the most probable.

[1] By Mr. Willis' method (*ante*, p. 662, foot note) the mechanical sediments of the Paleozoic age for the area under consideration corresponds to 6 billion mile-feet.

In dealing with the post-middle Cambrian mechanical sediments we have a somewhat different problem, but, as a whole, rapid deposition is indicated. For instance, the Eureka quartzite of the upper Ordovician is a bed of sandstone, varying from 200 to 400 feet in thickness, distributed over a wide area,—perhaps 50,000 square miles. It is made almost entirely of a white, clean sand that was deposited in so short an interval that the Trenton fauna in the limestone beneath it and in the limestones above it is essentially the same. The sand appears to have been swept rapidly into the sea and distributed by strong currents. The same is true of the 3,000 feet of the lower Carboniferous sand and the 2,000 feet in the upper portion of the Carboniferous, while the shales of the upper Devonian accumulated more slowly. In this connection we must bear in mind that during the long periods in which the calcareous sediments forming the limestones were being deposited, the tributary land areas were in all probability base-levels of erosion, and chemical denudation was preparing a great supply of mechanical material that, on the raising of the land, was rapidly swept into the sea and distributed. In this manner the time period of actual mechanical denudation was materially shortened, yet, on account of the manifestly slower deposition of the Devonian shales, the rate of denudation should be assumed as less than during Cambrian time.

In post-Cambrian time the area of the land surface was materially reduced by subsidence, which did not, however, greatly extend the Cordilleran sea, and it may fairly be estimated at 600,000 square miles. The depth of mechanical sediments already estimated is 5,000 feet, and their volume at two billion mile-feet. Dividing the volume by the area of erosion we get 3,300 feet as the depth of erosion required.

Again, applying different rates of erosion, with allowance for slow progress of degradation during Devonian time, we have:

Of this total the greater part, namely, two-thirds or 4 billion mile-feet, are of Cambrian age. Dividing this volume by the land area just given, 1,600,000 square miles, we get 2,500 feet as the depth of erosion during the formation of the Cambrian mechanical sediments. Assuming different rates of erosion we may obtain times differing as follows:

POST-CAMBRIAN MECHANICAL SEDIMENTS.

Rate of erosion over land area of 600,000 square miles.	Time required for removal of 3,300 feet.	Rate of deposition in sea of 400,000 square miles, for 5,000 feet of strata.
1 foot in 3,000 years, - -	9,900,000 years	1 foot in 1,980 years, or .006 inch per annum.
1 foot in 1,000 years, - -	3,300,000 years	1 foot in 660 years, or .09 inch per annum.
1 foot in 200 years, - - -	660,000 years	1 foot in 132 years, or .18 inch per annum.

The rate of one foot in 200 years is assumed as the most probable and 660,000 years as the time required for the removal and deposition of the 5,000 feet of post-Cambrian mechanical sediments.

There is one factor that may need to be taken into consideration in estimating the time duration of the deposition of the mechanical sediments of the Cambrian and pre-Cambrian of the northern portion of the Cordilleran sea that would materially lengthen the period. Dr. George M. Dawson describes the Nisconlith series, especially in the Selkirk range of British Columbia, as composed of "blackish argillite-schists and phyllites, generally calcareous, with some beds of limestone and quartzite, 15,000 feet."[1] It is correlated with the Bow River series, which contains, in the upper portion, the lower Cambrian fauna. The presence of these calcareous beds indicates a slower rate of deposition than we have estimated for the lower portion of the Cambrian series over the greater part of the Cordilleran sea; but as yet the correlation with the sediments of the Cordileran sea is not sufficiently well established to warrant our allowing a greater time period to the Cambrian on this account.

Estimates from Chemical Sedimentation.—We have estimated that the Paleozoic sediments of the Cordilleran sea contain 2,007,244,800 million tons (900 million mile-feet) of carbonate of lime, which was derived by organic or chemical agencies from the sea water to which it was contributed by the land. If oceanic circulation could be excluded from the problem we might pro-

[1] Bull. Geol. Soc. Amer., Vol. II., 1891, p. 168.

ceed directly to estimate the time required to obtain this amount of lime from the land area tributary to the Cordilleran sea. It may be well to make such an estimate on the basis that the area of denudation tributary to the Cordilleran sea in post-middle Cambrian time had 600,000 square miles from which 30,000,000 tons of carbonate of lime and 12,000,000 tons of sulphate of lime were derived per annum,[1] if we assume T. Mellard Reade's rate of erosion—of 50 tons of carbonate of lime and 20 tons of sulphate of lime per square mile per annum. If all of the 42,000,000 tons (equal to 18.8 mile-feet) per annum were deposited within the limits of the Cordilleran sea, it would have taken 47,790,000 years for the accumulation of the carbonate of lime now estimated to have been deposited in the Cordilleran sea. Such a result is manifestly a maximum based on the consideration of one set of phenomena. In addition, however, to this supply of calcium the geographic conditions appear to have been favorable to the free circulation of oceanic currents through the Cordilleran sea, and the temperature was favorable to extensive evaporation and to the development of organic life, as shown by the occurrence of corals in the middle and upper portions of the Paleozoic, from the Mackenzie river basin on the north to southern Nevada on the south. These conditions would reduce the time necessary for the deposition of the carbonate line.

Ocean water of the present time contains in solution 151.025000 tons of solid matter per cubic mile, which is divided among various salts. A comparison of the matter in the sea and river water shows that the sea contains 3.85 parts of magnesium to one of calcium, and river water contains three parts of calcium to one of magnesium. The silica and alumina of the river water disappears in sea water, while the sodium is accumulated. It is from these considerations and the fact that limestones are

[1] Messrs. Murray and Renard consider that organisms have the power of secreting the carbonate of lime from the sulphate of lime contained in the sea water by chemical reaction. For an account of the chemical action that takes place in the sea water, see report of the Deep-Sea Deposits of the Challenger Expedition.

so largely formed of carbonate of lime that I have taken the latter as a basis for estimates upon the rate of chemical sedimentation, an allowance being made for the presence of silica, alumina and magnesium in the limestones.

Rate of Deposition of Recent Deposits.—Of the rate of deposition in recent deposits Messrs. Murray and Renard state, in their report on the deep-sea deposits, that: "It must be admitted that at the present time we have no definite knowledge as to the absolute rate of accumulation of any deep-sea deposit, although we have some information and some indications as to the relative rate of accumulation of the different types of deposits among themselves. The most rapid accumulation appears to take place in the Terrigenous Deposits, and especially in the Blue Muds, not far removed from the embouchures of large rivers. Here no great time would seem to have elapsed since the deposit was formed, so far at least as the materials collected by the dredge, trawl, and sounding tube are concerned.

"Around some coral reefs the accumulation must be rapid, for, although pelagic species with calcareous shells may be numerous in the surface waters, it is often impossible to detect more than an occasional pelagic shell among the other calcareous debris of the deposits.

"The Pelagic Deposits as a whole, having regard to the nature and condition of their organic and mineralogical constituents, evidently accumulate at a much slower rate than the terrigenous deposits, in which the materials washed down from the land play so large a part. The Pteropod and Globigerina oozes of the tropical regions, being chiefly made up of the calcareous shells of a much larger number of tropical species, must necessarily accumulate at greater rate than the Globigerina oozes in extra-tropical areas or other organic oozes. Diatom ooze, being composed of both calcareous and siliceous organisms, has, again, a more rapid rate of deposition than the Radiolarian ooze, while in a Red Clay there is a minimum rate of growth."[1]

[1] Report on the scientific results of the voyage of H. M. S. Challenger; Deep-Sea Deposits. 1891, pp. 411-412.

Professor James D. Dana estimates that the rate of increase of coral reef limestone formations, where all is most favorable, does not exceed perhaps a sixteenth of an inch in a year, or five feet in a thousand years. Of this he says, "And yet such limestones probably form at a more rapid rate than those made of shells."[1]

Messrs. Murray and Irvine, in their valuable paper on coral reefs and other carbonate of lime formations in modern seas, calculate the total amount of calcium in the whole ocean to be 628,340,000 million tons; also they estimate that 925,866,500 tons of calcium are carried into the ocean from all the rivers of the globe annually. At this rate it would take 680,000 years for the river drainage from the land to carry down an amount of calcium equal to that at present existing in solution in the whole ocean. They say further: "Again, taking the 'Challenger' deposits as a guide, the amount of calcium in these deposits, if they be 22 feet thick, is equal to the total amount of calcium in solution in the whole ocean at the present time. It follows from this that, if the salinity of the ocean has remained the same as at present during the whole of this period, then it has taken 680,000 years for the deposits of the above thickness, or containing calcium in amount equal to that at present in solution in the ocean, to have accumulated on the floor of the ocean."[2] According to this calculation the mean rate of accumulation over existing oceanic areas is $\frac{22}{680000}$. or .000032 feet per annum.

Was the Deposition of Chemical Sediment More Rapid in Paleozoic Time?—It has been claimed that the quantity of lime poured into the ocean in earlier times was greater than during the later epochs of geological history,—this arising from the more rapid disintegration of the Archean, crystalline and volcanic rocks. It is undoubtedly a fact that the ocean was stocked in Archean and Algonkian time with matter in solution that produced salinity, but we have no evidence from chemical precipitation that more

[1] Corals and Coral Islands, 3rd Ed., 1890, pp. 396-397.

[2] Proc. Royal Soc., Edinburgh, Vol. 17, 1890, p. 101.

calcium was poured into it than could be retained in solution. The Laurentian limestones are crystalline, but, as has been shown, this texture is consistent with either chemical or organic origin. The unaltered limestones in the Algonkian rocks of the Colorado Cañon section show traces of life in thin sections, and they may be, to a great extent, of organic origin. There is no evidence in the texture, bedding or composition of these ancient limestones to indicate that they were deposited under conditions of salinity or of supply differing materially from those of the present, and I do not find that we have reason to believe that the deposition of the carbonate of lime was more rapid in the Paleozoic than during the Mesozoic and Cenozoic times, even though the supply from the land may have been greater. Where the conditions were favorable for the deposition of lime, as in the Cretaceous sea of northern Mexico, we find evidence of an immense accumulation of calcareous sediments. Of the amount of calcareous deposits in the seas outside of the continental areas that are not open to our inspection, we know nothing; but judging from the deposition that is going on to-day in the great oceans, the accumulation of calcareous sediment has gone on in the past as steadily and uninterruptedly as at present, subject to varying conditions of temperature, life, depth of water, etc.

Area of Deposition in Paleozoic Time.—We have no proof that the salinity of the sea or the amount of calcium contained in it has varied from age to age since Algonkian time. If it has not, all of the calcium poured into the ocean during 2,000,000 years would have about equaled the amount now contained in the limestones of that area. We have, however, to account for the calcium deposited in the interior Mississippian sea and the seas over other portions of this continent and other continental areas, and on portions of the floor of the ocean that are now accessible for observation. It is also to be considered that the land areas subject to denudation in Paleozoic time were, in all probability, of no larger extent than at the present time.

The area of dry land to-day is estimated to be 55,000,000 square miles, and of oceans 137,200,000 square miles.[1]

Mr. T. Mellard Reade estimates the area of the Paleozoic formations of Europe at 645,600 square miles in the total area of 3,720,500 square miles. His estimate of the Paleozoic area is of that which is exposed at the present time, and does not include that which is concealed beneath other formations. I think it will be a minimum estimate to consider that an equal area is covered by the later formations, which, with that exposed, would give in round numbers 1,290,000 square miles,—or one-third of the land area of Europe. In North America nearly one-half of the total area was covered by the Paleozoic sea; in South America it was considerably less; and we know too little of the Asiatic and African continents to place any estimate upon their Paleozoic areas. I think, however, if we take one-fourth of the present land area as the territory covered by the Paleozoic seas we shall be considerably within the actual amount, even if we add to the surface of the continents the margins of the continental platforms now beneath the sea. Deducting the one-fourth from the total land area, there remain 41,250,000 square miles as the land area undergoing denudation during Paleozoic time. It may be claimed that large areas in the archipelago region of the Pacific and in the Arctic ocean may have been land areas at that time. To meet this, 8,750,000 square miles may be added to the 41,250,000, giving a total of 50,000,000 square miles as the land area of Paleozoic time.

The estimated areas of the various deep sea deposits of to-day, containing a large percentage of the carbonate of lime, are as follows: Globigerina ooze, 49,520,000 square miles, mean percentage of carbonate of lime, 64.53; Pteropod ooze, 400,000 square miles, percentage of carbonate of lime, 79.26; Coral mud and sand, 2,556,000 square miles, mean percentage of carbonate of lime, 86.41. In addition to this, Diatom ooze covers an area of 10,880,000 square miles, with 22.96 percentage of carbonate of lime; and the mean percentage of carbonate of lime in the

[1] Dr. JOHN MURRAY: Scottish Geog. Mag., Vol. 4, 1888, p. 40.

Blue Mud and other terrigenous deposits that cover 16,050,000 square miles is 19.20. If we consider only those deposits containing over 64 per cent. of carbonate of lime, we have 52,500,000 square miles, over which there is at the present time a deposition of the carbonate of lime being made. We have roughly estimated that in Paleozoic time the area of the Paleözoic sea, in which deposits were being accumulated, was over 13,000,000 square miles. It does not appear that there is any good reason to suspect that the area of deposition of the carbonate of lime in the open ocean during Paleozoic time was not fully equal to that of the present time. Adding this area of 52,500,000 to the 13,750,000, we have over 66,000,000 square miles as the probable area in which calcium was being deposited in Paleozoic time.

Conditions favorable for a rapid deposition of the carbonate of lime.—The condition most favorable for the rapid accumulation or deposition of the carbonate of lime through organic or mechanical agency is warm water and a constant supply of water through circulation by currents; this is shown by the immense abundance of life where the margin of the continental plateau is touched by the Gulf Stream. Another favorable condition is the supply of carbonate of lime by river water directly into the ocean in the vicinity where the deposition of lime is going on either through organic or inorganic agencies. This is well illustrated by the conditions produced by the Gulf Stream. The oceanic currents, passing along the northeastern coast of South America, sweep the waters of the Amazon through the Caribbean sea into the Gulf of Mexico, where they meet the vast volume of water coming from the Mississippi. These are poured out through the narrow straits between Florida and Cuba and carried northward over the sloping margin of the continental plateau. Under such favorable conditions the deposit must be much greater than in areas where there is little circulation and the supply of calcium is limited to the average which is contained in sea water. If to the preceding there is added extensive evaporation within a partially enclosed sea, the rate of deposition of matter in solution will be largely increased.

The area over which calcareous depositions was going on during Paleozoic time we have estimated at 66,000,000 square miles, which includes the areas of the seas over the continental platforms and those of the surrounding oceans. As the conditions appear to have been more favorable for the deposition of lime in the Cordilleran aud Appalachian seas, we will assume that it was four times that of the open ocean.[1] With a land area of 50,000,000 square miles (*ante* p. 670) and a rate of chemical denudation of 70 tons per square mile per annum, the total calcium contributed to the ocean per year during Paleozoic time would be 3,500 million tons or 3.78 times as much as that estimated for per annum at the present time, which is 925,866,500 tons (*ante* p. 668). This would have provided 50.7 tons for deposition per annum per square mile in the 65,000,000 square miles of ocean and seas and 202.8 tons for deposition per annum per square mile in the 400,000 square miles of the Cordilleran and 600,000 square miles of similar seas. On this basis 81,120,000 tons (36.4 mile-feet) were contributed per annum from the ocean water to the deposit in the Cordilleran sea; adding to this the 42,000,000 tons (18.8 mile-feet) contributed per annum by the denudation of the surrounding area to the Cordilleran sea, we have 128,120,000 tons (55.2 mile-feet) as the amount available for deposit per annum in the Cordilleran sea. At this rate it would have required 16,300,000 years to have deposited the 2,007,244,800 million tons (900 million mile-feet) of *calcium* in the Cordilleran sea; adding to this the 1,200,000 years estimated for the deposition of the mechanical sediments, we have a total of 17,500,000 years as the duration of Paleozoic time.

In reviewing the preceding estimates we must consider that,

[1] Under the reduction of 50 per cent. for the interbedded and intermingled mechanical sediments and 25 per cent. for other material than calcium deposited from solution, the apparent amount of calcium deposited in the Cordilleran sea was greatly reduced. If this same ratio of reduction is applied to other Paleozoic limestone areas, I doubt if over 1,000,000 square miles will be found to contain as large an average amount of calcium per square mile as the Cordilleran area. On this account 1,000,000 square miles is the area taken for the greater rate of deposition of calcium during Paleozoic time.

throughout, I have increased the various factors above those usually accepted: thus, for mechanical sedimentation, one foot in 200 years is used. If the usually accepted average of one foot in 3,000 years is taken the time period must be increased fifteenfold (21,000,000 years), or the area of denudation from 1,600,000 square miles to 24,000,000—or three times the present area of the North American continent.

In the estimate for the amount of chemical denudation the largest average is taken—70 tons of calcium per square mile per annum—and the assumption made that all calcium derived from the adjoining drainage was deposited within the Cordilleran sea. Again, the total supply provided per annum to ocean waters of Paleozoic time is taken as 3.78 times greater than the amount annually contributed to ocean waters to-day; of this, four times as much is assumed to have been taken out per annum per square mile as was taken by the remaining area in which calcium was being deposited.

The area of the Cordilleran sea is given as 400,000 square miles, but it was probably 600,000, if not much more. It may be claimed that the area tributary to the Cordilleran sea was greater than I have estimated. The evidence, such as it is, is against such a view. As a whole I think the estimate of 17,500,000 years for the duration of Paleozoic time in the Cordilleran area is below the minimum rather than above it.

If the estimated rate of the deposition of coral limestones—five feet in 1,000 years—given by Prof. Jas. D. Dana is correct, the 19,000 feet of Paleozoic limestone in central Nevada would have required 3,800,000 years to have accumulated under the most favorable local conditions surrounding a coral reef. With the exception of large deposits of corals in Devonian rocks no appearance of a coral reef is recorded in the Cordilleran area.

TIME-RATIOS OF GEOLOGIC PERIODS.

The time-ratio adopted by Prof. James D. Dana for the Paleozoic, Mesozoic and Cenozoic periods is: 12, 3, and 1, respectively[1]. Prof. Henry S. Williams applies the term *geochronology*,

[1] Manual of Geology, 1875, p. 586.

giving the standard time-unit used the name *geochrone*. The geochrone used by him in obtaining a standard scale of geochronology is the period represented by the Eocene. His time-scale gives 15 for the Paleozoic; 3 for the Mesozoic; and 1 for the Cenozoic, including the Quaternary and the Recent.[1]

The Rev. Samuel Haughton obtained the following time-ratios from the maximum thickness of strata as they occur in Europe:

SCALE OF GEOLOGICAL TIME.

Period.	From Theory of Cooling Globe.	From Maximum Thickness of Strata.
Azoic	33.0 per cent.	34.3 per cent.
Paleozoic	41.0 "	42.5 "
Neozoic	26.0 "	23.2 "
Total	100.0 per cent.	100.0 per cent.

He draws from this the principle—"*The proper relative measure of geological periods is the maximum thickness of the strata formed during these periods.*"[2]

In considering the time-ratios for the Paleozoic, Mesozoic, and Cenozoic rocks of the North American continent, as given by Dana and Williams, I think that a too small proportion has been given to the Mesozoic and Cenozoic. In the Mesozoic of the western-central area occur the coal deposits of the Laramie series and the great development of limestone (from 10,000 to 20,000 feet) in the Cretaceous of Mexico. The limits of this paper do not permit of a discussion of the available data bearing upon geologic time-ratios; but from a comparison of the Paleozoic, Mesozoic, and Cenozoic strata and the geologic phenomena accompanying their deposition, I would increase the comparative length of the Mesozoic and Cenozoic periods so that the time-ratios would be: Paleozoic, 12; Mesozoic, 5; Cenozoic, including Pleistocene, 2.

DURATION OF POST-ARCHEAN GEOLOGIC TIME.

Taking as a basis 17,500,000 years for Paleozoic time and the time-ratios, 12, 5, and 2 for Paleozoic, Mesozoic, and Ceno-

[1] Journal of Geology, Chicago, Vol. I., 1893, pp. 294-295.

[2] Nature, Vol. 18, 1878, p. 268.

zoic (including Pleistocene) respectively, the Mesozoic is given a time duration of 7,240,000 years, the Cenozoic of 2,900,000 years, and the entire series of fossiliferous sedimentary rocks of 27,650,000 years. To this there is to be added the period in which all of the sediments were deposited between the basal crystalline Archean complex and the base of the Paleozoic. Notwithstanding the immense accumulation of mechanical sediments in this Algonkian time, with their great unconformities and the great differentiation of life at the beginning of Paleozoic time, I am not willing with our present information to assign a greater time period than that of the Paleozoic—or 17,500,000 years. Even this seems excessive. Adding to it the time period of the fossiliferous sedimentary rocks, the result is 45,150,000 years for post-Archean time. Of the duration of Archean or pre-Algonkian time, I have no estimate based on a study of Archean strata to offer. If we assume Haughton's estimate of 33 per cent. for the Azoic period and 67 per cent. for the sedimentary rocks, Archean time would be represented by the period of 22,250,000 years. In estimating for the Archean, Haughton included a large series of strata that are now placed in the Algonkian of the Proterozoic of the United States Geological Survey; and I think that his estimate is more than one-half too large; if so, ten million years would be a fair estimate, or rather conjecture, for Archean time.

Period.	Time Duration.
Cenozoic, including Pleistocene - -	2,900,000 years
Mesozoic - - - - - - - -	7,240,000 "
Paleozoic - - - - - - -	17,500,000 "
Algonkian - - - - - - -	17,500,000 "
Archean - - - - - - -	10,000,000(?)"

It is easy to vary these results by assuming different values for area and rate of denudation, the rate of deposition of carbonate of lime, etc.; but there remains, after each attempt I have made that was based on any reliable facts of thickness, extent and character of strata, a result that does not pass below 25,000,000 to 30,000,000 years as a minimum and 60,000,000 to

70,000,000 years as a maximum for post-Archean Geologic time. I have not referred to the rate of development of life, as that is virtually controlled by conditions of environment.

In conclusion, geologic time is of great but not of indefinite duration. I believe that it can be measured by tens of millions, but not by single millions or hundreds of millions of years.

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